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PROPERTIES OF OPTICALLY THICK CORONAE AROUND ACCRETING BLACK HOLES

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Abstract. Accreting black holes are complex sources exhibiting several spectral components (disc, jet, hot corona etc). The exact nature and the interplay between these components is still uncertain, and constraining the accretion flow in the vicinity of the compact object has become a key problem to understand the general physics of accretion and ejection.

In the past years, the X-ray spectra of several X-ray binaries and AGN have suggested the existence of a new type of coronae in the inner part of their accretion disk. These coronae are warm (about 1 keV) and have Thomson optical depths of about $\tau \approx 10$, much larger than the standard comptonizing medium inferred in black hole systems. However, simple radiative models based on the diffusion approximation are unable to sustain a large temperature over such high optical depths, therefore questioning existence of these thick coronae.

Here we investigate the radiative and hydrostatic properties of slabs, thick coronae covering a standard accretion disc. A precise modelling of the radiation transfer shows that the observed temperature inversion can be reproduced, provided that most of the accretion power is dissipated in this upper layer and that the medium is strongly magnetised.

Keywords: Radiative transfer, Scattering, Methods: analytical, Accretion, accretion disks

1 Introduction

The X-ray spectrum of accreting black holes is usually modelled with several components. The softer component is a multi-temperature blackbody originating from the accretion disk. The inner disk temperature is about 10 eV in AGN and 1 keV in X-ray binaires. At higher energy, the spectrum is often modelled with a comptonisation component resulting from the up-scattering of cold disc photons in a hot corona located in the innermost parts of the accreting system. The coronal temperature and optical depth are similar in AGN and X-ray binaries in their low-hard state, namely $k_BT \sim 100$ keV and $\tau \sim 1$ respectively.

These two components, with the addition of reflection features, are able to reproduce many observations of accreting black holes. However, many sources have shown an excess in the intermediate band. In X-ray binaires, this excess is seen in the $2 - 10$ keV band when the sources are in the *very high state*. Although this component can also been explained by a complex structure of the accretion disk (i.e. different from a standard disc, Shakura & Sunyaev 1973), or a contribution from the jet, it has been proposed that it results from comptonisation in a warm ($k_BT \sim 1$ keV) and optically thick ($\tau \sim 3 - 10$) corona covering the inner accretion disc (e.g. Zhang et al. 2000). The issue is most common in AGN, where the so-called *soft excess* is observed below 2 keV. Here also, several explanations have been proposed, as blurred, ionised reflection (Fabian et al. 2004; Crummy et al. 2006), smeared absorption by an outflowing medium (Gierliński & Done 2006; Schurch et al. 2009). However comptonisation in a warm and optically thick corona sucessfuly allows to reproduce the broad band spectrum of many sources, such as NGC5548 (Magdziarz et al. 1998), PG1211+143 (Janiuk et al.

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2001), Mrk 359 (Czerny et al. 2003), RE1034+396 (Done et al. 2012), Mrk 509 (Petrucci et al. 2013), and many others (Jin et al. 2012). The temperature is similar to that in X-ray binaires ($k_B T \sim 1$ keV), the optical depth is always much larger than unity ($\tau \sim 10-20$), and the covering factor is large, suggesting a slab, sandwich-like geometry.

Hot atmospheres are common in astrophysical sources (e.g. in the sun) and can be expected from several processes (e.g. enhanced dissipation, external illumination). However such hot upper layers are commonly thought to remain optically thin. This simple result is based on two facts:

- First, in a plane-symmetric, sandwich geometry, radiation can only escape from the upper layers, so that the radiation flux is directed upward, away from the disk-atmosphere boundary.
- Second, when a medium is optically thick ($\tau >> 1$), radiation cannot escape freely. It is trapped and only diffuses slowly out of the medium. Moreover, the local spectrum at some altitude is a blackbody with the local temperature. In this diffusion approximation, the local radiation energy density and the local flux scale as $U_{\rm rad} \propto T^4$ and $F_{\rm rad} \propto -T^3 dT/dz$ respectively, where z is the altitude measured from the disc mid plane.

Therefore, the temperature can only decrease with altitude from the disc-atmosphere boundary, in contradiction with observations of a warm and thick upper layers.

Here is a summary of a recent work we have done on this problem (Rozanska et al. 2015). We show that the diffusion is not valid with the inferred properties of warm and thick coronae, and we perform a more precise analysis of radiation transfer in such layers. We fist derive the properties of the radiation field by solving the radiation transfer equation (section 2). Then, we derive the temperature profile by solving the energy equation (section 3). And last, we compute the hydrostatic structure of the corona. Conclusions follow in the last section.

2 Radiation profile

The diffusion approximation is valid for optically thick media. When both scattering and absorption are involved, it means that the *effective* optical depth $\tau_* \approx \sqrt{\tau_a(\tau_a+\tau_s)} >> 1$ is much larger than unity (where τ_a and τ_s are the absorption and scattering optical depth respectively). Here, comptonisation models of the X-ray excess lead to *Thomson* optical depths as large as $\tau_s \approx 10-20$. However, as the inferred temperature is also large, the absorption optical depth (dominated by bremmstrahlung absorption) is small, and the effective optical depth remains moderate. The diffusion approximation therefore does not hold and the radiation transfer equation must be solved.

In the following, we define τ the Thomson optical depth as measured downwards, from the atmosphere surface. We consider an atmosphere of total, Thomson optical depth τ_c. For seek of simplicity, we assume a uniform dissipation per unit optical depth and solid angle: Q. The total power dissipated in the atmosphere is $F_c = 4\pi Q \tau_c$. The atmosphere covers a standard disk with vertically integrated dissipation F_d. The coronal dissipation is parametrised by the ratio

$$\chi = F_c/F_{\rm tot} \tag{2.1}$$

where $F_{\rm tot} = F_c + F_d$ is the total dissipation. The slab, grey (frequency integrated) radiation transfer equation for specific intensity I then reads: $-\cos\theta dI/d\tau = J - I + Q$, where J is the angle-averaged intensity and angle θ is measured from the vertical direction. It can be solved by computing its first moments and using a closure relation. The first moment gives an equation on the flux: $-dF/d\tau = 4\pi Q$. With the boundary condition at the base $F(\tau_c) = F_d$, the solution is: $F/F_{\rm tot} = 1 - \chi\tau/\tau_c$. The flux increases upwards because of local dissipation. The second moment gives an equation on the radiation pressure: $cdP_{\rm rad}/d\tau = F$, where c is the speed of light. Using the Eddington approximation ($U_{\rm rad} = 3P_{\rm rad}$), and assuming no incoming flux at the atmosphere surface leads to the upper boundary condition $P_{\rm rad}(0) = 2F_{\rm tot}/(3c)$, which gives the solution:

$$cP_{\rm rad}/F_{\rm tot} = 2/3 + \tau - \chi\tau^2/(2\tau_c) \tag{2.2}$$

As expected, the radiation pressure decreases with altitude since radiation can only escape from the top.

3 Temperarure profile

As the effective optical depth is not expected to be larger than unity, the temperature does not scale as $T \propto U_{\rm rad}^{1/4}$. Rather it is computed by assuming that Compton up-scattering is the dominant cooling mechanism:

Model number	$\beta_{\rm m}$	$F_{\rm Edd}/F_{\rm tot}$	χ	τ_c	$kT_{\rm av}$ (keV)
1	0	1	0.98	5.21	3.91
2	50	1	0.98	19.9	0.42
3	50	6	0.98	8.76	1.68
4	50	1	0.4	15.9	0.23
5	50	3	0.4	7.08	0.88
6	50	1	0.02	9.28	2.68 $\times 10^{-2}$

Table 1. Properties of models shown in other figures.

$Q = Q_c = 4c(U_{\rm rad}/4\pi)(k_BT/m_ec^2)$, where m_e is the electron mass. This gives:

$$\frac{k_BT}{m_ec^2} = \frac{\chi}{12\tau_c}\left(\frac{2}{3} + \tau - \frac{\chi}{2}\frac{\tau^2}{\tau_c}\right)^{-1} \tag{3.1}$$

Examples of temperatures profiles are shown in Fig. 1 (left) for various values of τ_c and χ. As the radiation

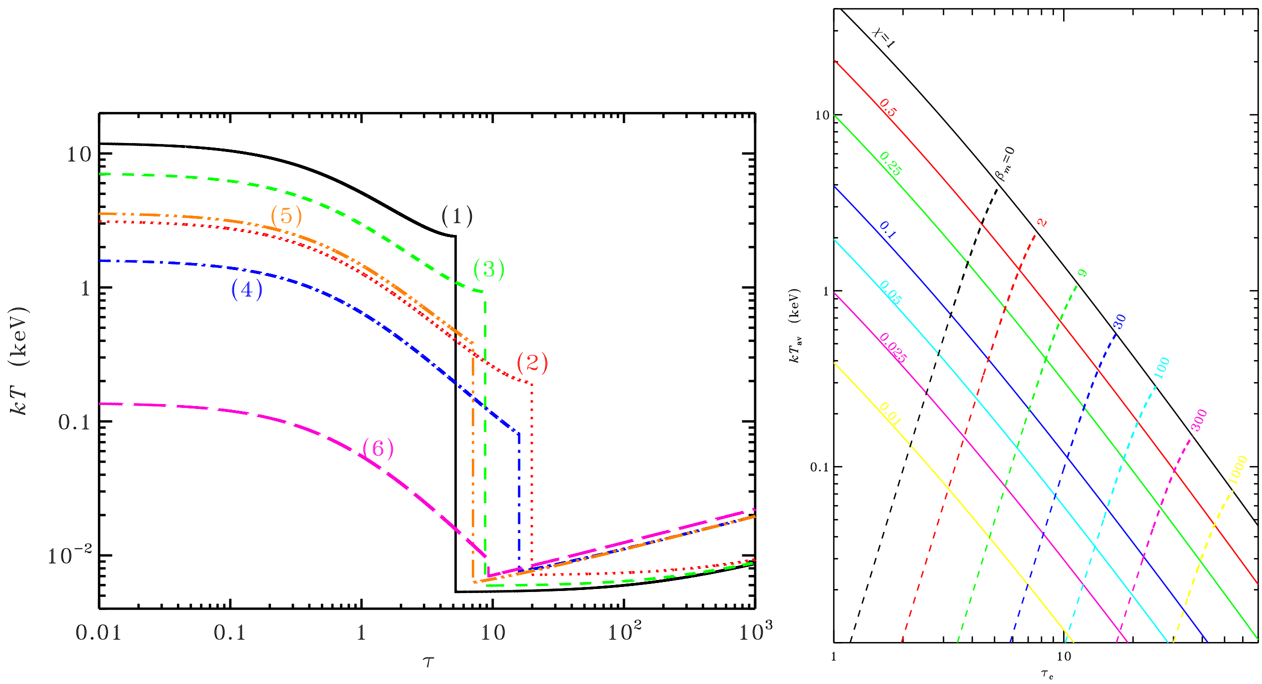

Fig. 1. Left: Local temperature as a function of the Thomson optical depth for models defined in Tab. 1. Temperature in the underlying disk was computed using the diffusion approximation with negligible dissipation. **Right:** Average temperature of the corona, as a function of its optical depth τ_c (solid lines) for different values of the dissipation χ. Dashed lines show the maximal optical depth above which free-free cooling starts dominating over Compton cooling.

field is weaker in the upper layers of the atmosphere, Compton cooling is less efficient, producing a larger temperature. In Compton-dominated atmospheres, a temperature inversion is therefore found, as suggested by observations. Interestingly, the temperature remains bounded, even when most of the accretion power is dissipated in the corona. The surface temperature is: $k_BT_0 = 6\chi(\tau_c/10)^{-1}$ keV. Even with $\chi = 1$, it cannot not exceed a few keV. Moreover, the observed spectrum is likely to be comparable to the comptonisation in a uniform medium with average temperature $T_{\rm av} = \int_0^{\tau_c} Td\tau/\tau_c$, smaller than the surface temperature. This average temperature is shown in Fig. 1 (right). It is found that atmospheres with temperature of $k_BT_{\rm av} \sim 1$ keV and Thomson optical depth $\tau_c \leq 15$ can be reproduced, provided that most of the dissipation occurs in this layer ($\chi \sim 1$).

4 Hydrostatic structure

In static equilibrium, the total pressure must balance gravity: $dP/d\tau = GMz/(\kappa_{es}R^3)$ where G is the gravitational constant, M the black hole mass, R the radial distance to the black hole, and κ_{es} the electron scattering opacity. The total pressure is composed by radiation pressure $P_{\rm rad}$, and gas pressure $P_{\rm gas}$. We also include a possible contribution P_B of the magnetic field, with uniform ratio $\beta_m = P_B/P_{\rm gas}$. For simplicity, we assume that the atmosphere is thin, at some fixed altitude z_c, so that gravity is also uniform within the entire atmosphere. For a given coronal altitude z_c, matter can only be in static equilibrium as long as the total flux $F_{\rm tot}$ remains below a critical flux $F_{\rm Edd}$ (akin a slab version of the Eddington limit) and given by: $\kappa_{es}F_{\rm Edd}/c = GMz_c/R^3$. Solving the hydrostatic equilibrium with a no gas-pressure boundary condition at the atmosphere surface yields the following profiles for the gas pressure and density:

$$\frac{cP_{\rm gas}}{F_{\rm tot}} = \frac{\tau}{1+\beta_m}\left(\frac{F_{\rm Edd}}{F(\tau)} - 1 + \frac{\chi}{2}\frac{\tau}{\tau_c}\right) \tag{4.1}$$

$$\frac{m_e}{\mu m_p}\frac{c^3\rho}{F_{\rm tot}} = \frac{12\tau_c}{\chi}\frac{\tau}{1+\beta_m}\left(\frac{F_{\rm Edd}}{F(\tau)} - 1 + \frac{\chi}{2}\frac{\tau}{\tau_c}\right)\left(\frac{2}{3} + \tau - \frac{\chi}{2}\frac{\tau^2}{\tau_c}\right) \tag{4.2}$$

Examples of density profiles are shown in Fig. 2. Both quantities decrease with altitude. Deep in the atmosphere,

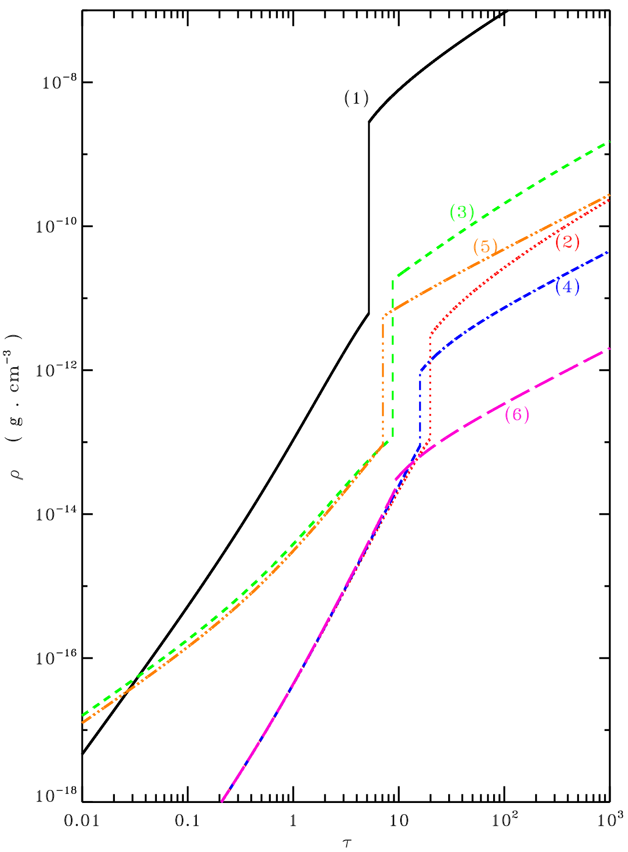

Fig. 2. Local gas density as a function of Thomson optical depth, for the models presented in Tab. 1. Temperature in the underlying disk was computed using the diffusion approximation with negligible dissipation.

the temperature is the lowest and the density the largest, so that free-free cooling is the most efficient mechanism. For a temperature inversion to remain possible, the latter has to remain negligible compared to Compton cooling. For given dissipation rate χ, magnetic ratio β_m, and altitude z_c, comparing the two cooling rates gives a maximal possible optical depth. This is shown in dashed lines in Fig. 1 (right). It is found that in unmagnetised coronae, the maximal optical depth is about $\tau_c = 5 - 6$ in the most favorable situation (i.e. for maximal dissipation $\chi = 1$, and lowest altitude $F_{\rm tot} = F_{\rm Edd}$). This is too thin to account for the observed properties of the observed coronae. However, at a given altitude, any additional magnetic pressure reduces the gas pressure, hence the free-free cooling. Super-equipartition fields with $P_B/P_{\rm gas} = 50 - 100$ allow for warm corona with $k_B T_{\rm av} \approx 1$ keV up to $\tau_c = 10 - 15$.

5 Conclusions

We have investigated the properties of dissipative, warm ($k_B T \sim 1$ keV), optically thick ($\tau_{es} \sim 10-20$) coronae on the top of standard accretion discs. Contrary to what is usually done, the diffusion approximation cannot be used in such hot media and the radiation transfer equation must be solved. This gives the profiles for flux and radiation energy density. In turn, balancing the dissipation with Compton cooling determines the temperature. We find that the dissipation can sustain a hot temperature down to optical depths compatible with observations, provided that most of the accretion power is dissipated in the atmosphere (as oppose as in the disc). Solving the hydrostatic equation determines the gas pressure and density. We find that these quantities remain low enough for the Compton cooling to be the dominant cooling mechanism in the entire atmosphere, only if the medium is strongly magnetized.

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